Modelling and Simulation of Doubly Fed Induction Generator for the Wind Energy Conversion System

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Abstract: Over the past few decades, there has been an increasing use of induction generator particularly in wind power applications. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor now operates as a generator, and sends power back to the electrical grid. Based on the source of reactive power induction generators can be classified into two types namely standalone generator and Grid connected induction generator. In case of standalone IGs the magnetizing flux is established by a capacitor bank connected to the machine and in case of grid connection it draws magnetizing current from the grid.

This paper explicitly deals with the study of grid connected induction generators where frequency and voltage of the machine will be dictated by the electric grid. Among these types of IGs, Doubly Fed Induction Generator (DFIG) wind turbines are nowadays increasingly used in large wind farms because of their ability to supply power at constant voltage and frequency. Modern control techniques such as Vector control and MFC (magnitude and frequency control) are studied and some of proposed systems are simulated in MATLAB- SIMULINK environment.

1. Introduction

1.1 Wind Power:

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, windmills for mechanical power, wind pumps for water pumping, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world ‘s rapid growing source of energy.

1.2 Why wind energy?

The majority of electricity is generated by burning coal, rather than more eco-friendly methods like hydroelectric power. This use of coal causes untold environmental damage through CO2 and other toxic emissions. The energy sector is by far the biggest source of these emissions, both in the India and globally, and if we are to tackle climate change it is clear we need to move away from burning limited fossil fuel reserves to more sustainable and renewable sources of energy.

1.3 Benefits of Wind Power:

Wind power has many advantages that make it a lucrative source of power for both utility- scale and small, distributed power generation applications. The beneficial characteristics of wind power include:

• Clean and endless fuel—Wind power doesn’t produce any emissions and is not run down with time. A one megawatt (1 MW) wind turbine for one year can displace over 1,500 tons of carbon dioxide, 6.5 tons of sulphur dioxides, 3.2 tons of nitrogen oxide, and 60 pounds of mercury (based on the U.S. average utility generation fuel mix).

• Local financial development—Wind plants can provide a firm flow of income to landowners who lease their land for wind development, while increasing property tax revenues for local communities.

2.1 Wind Energy Conversion System:

Wind energy can be harnessed by a wind energy conversion system, composed of wind turbine blades, an electric generator, a power
electronic converter and the corresponding control system. Fig. 2.1 shows the block diagram of basic components of WECS. There are different WECS configurations based on using synchronous or asynchronous machines, and stall-regulated or pitch-regulated systems. However, the functional objective of these systems is the same: converting the wind kinetic energy into electric power and injecting this electric power into a utility grid.

Fig. 2.1: Block diagram of a WECS

2.2 The Wind Resource:

The main consideration for siting a wind project in a certain site is the wind resource. Other considerations include site accessibility, terrain, land use and proximity to transmission grid for grid-connected wind farms. The main sources of the global wind movements are the earth rotation, regional and seasonal variations of sun irradiance and heating. Local effects on wind include differential heating of the land and the sea (land heats up faster), topographical nature such as mountains and valleys, existence of trees and artificial obstacle such as buildings.

At any location wind is described by its speed and direction. The speed of the wind is measured by anemometer in which the angular speed of rotation is translated into a corresponding linear wind speed (in meters per second or miles per hour). A Standard anemometer averages wind speed every 10 minutes. Wind direction is determined by weather vane.

The annual available wind energy is obtained by studying wind speed distribution. Weibull [2] probability or frequency distribution function is used to describe the variation in wind speed and it is given by [2]

$$f(v) = \frac{k}{a} \left(\frac{v}{a}\right)^{k-1} e^{-\left(\frac{v}{a}\right)^{k}}$$

(2.1)

At most sites, wind speed has the Rayleigh distribution which is a special case of Weibull distribution with $k=2$. This makes Rayleigh distribution a simple and accurate representation for wind speed with only the scale parameter $(a)$. The frequency of a wind speed band over a period of one year is found from wind speed data by

$$f = \frac{\text{number of hours per year the wind is between } v + dv}{dv}$$

(2.2)

Mean wind speed over the period of time is defined as the total area under the $f-v$ curve integrated from $v = 0$ to $\infty$ and divided by the total number of hours in the period ($365 \times 24 = 8760$ if the period is one year). The approximate annual mean speed is given by [9]

$$\bar{v} = 0.9 a$$

(2.3)

Hence, given the mean wind speed for a site and assuming $a = \bar{v}$ the Rayleigh distribution would be

$$f(v) = \frac{2}{\bar{v}^2} v e^{-\left(\frac{v}{\bar{v}}\right)^2}$$

(2.4)

Fig. 2.2. It is noted that the curve moves to the right for greater mean wind speeds (also greater value of shape parameter $a$) which means more days have high winds and hence a better potential wind energy revenue.

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Fig. 2.2 Rayleigh distribution functions for three different mean wind speeds.
2.3 Power Production:

The mechanical power of the wind passing an area of $A$ with speed $v$ is

$$p = \frac{1}{2} \rho Av^3 \quad (2.5)$$

It can be noted from the previous equation that the power of the wind varies linearly with the air area swept by rotor blades and with the cube of wind speed.

Assuming constant pressure and hence constant air density, the mass air flow is the same after and before the turbine

$$\frac{dm}{dt} = \frac{d}{dt}(\rho \cdot V) = \rho \frac{dV}{dt} = \rho \cdot A \cdot V \quad (2.6)$$

Where $V$ is the air volume and $v$ is the wind speed at the height of the turbine rotor. Moreover, $v$ is the average of winds speeds $v_1$ and $v_2$. That is,

$$v = \frac{v_1 + v_2}{2} \quad (2.7)$$

And the mechanical power taken from or extracted the wind after passing through the turbine,

$$p_T = \frac{1}{2} \rho A(v_1^2 - v_2^2)(v_1 + v_2) \quad (2.8)$$

The power content of wind passing through the area $A$ in the absence of the turbine is

$$p = \frac{1}{2} \rho Av^3 \quad (2.9)$$

Hence, the power coefficient $c_p$ or rotor coefficient which is the ratio between $P_T$ and $P$ is found.

$$c_p = \frac{p_T}{p} = \frac{1}{2} \left(1 - \frac{v_2^2}{v_1^2}\right) \left(1 + \frac{v_2^2}{v_1^2}\right) \quad (2.10)$$

That represents the fraction of the upstream wind power that is extracted by the rotor blade. It can be shown that $c_p$ is at its maximum when

$$\frac{v_2}{v_1} = \frac{1}{3} \quad (2.11)$$

Which is the ideal wind speed ratio, the maximum power coefficient will be

$$c_{p_{\text{max}}} \approx 0 \cdot 593 \quad (2.12)$$

This is often called Betz Power Coefficient and it means that theoretically about 60% of the wind power is taken by the turbine if it slows the air to one-third of its original speed. However, practical wind turbines have power coefficient values ranging from 0.4 to 0.5 for modern high-speed turbines and between 0.2 to 0.4 for low speed turbines with more blades [9]. The efficiency of the wind turbine would then be the ratio of the power taken to the ideal usable power

$$\eta = \frac{P_T}{c_p_{\text{max}} P} = \frac{c_p P}{c_{p_{\text{max}}} P} = \frac{c_p}{c_{p_{\text{max}}}} \quad (2.13)$$

In summary, the maximum power output of the turbine per square meter of rotor swept area is (assume rotor coefficient equal to $\frac{1}{2}$)

$$P_{\text{max}} = \frac{1}{2} \frac{dA}{dt} = \frac{1}{4} \rho V^3 \quad (2.14)$$

2.4 Estimating Annual Energy Consumption:

It has been shown that the power extracted by the rotor is proportional to the cube of wind speed, therefore it is useful to define a new value called room mean cube (RMC) of the wind speed which
gives better representation to the energy collected over a year

\[ V_{RMC} = \sqrt[2]{\frac{\int_{0}^{R_M} \rho f(v) v^2 dv}{365 \times 24}} \]  
\[(2.15)\]

Where the \( f(v) \) is the frequency distribution function for wind speed at that location (as mentioned previously a Rayleigh function with corresponding scale parameter \( a \) best fits wind speed frequency data for most sites).

Therefore, the annual average power generation (in watts per square meters of rotor blades swept area) is

\[ P_{T_{max}} = \frac{1}{2} \rho V_{RMC}^3 \]  
\[(2.16)\]

And the annual energy production is found as

\[ E = \frac{1}{2} \rho V_{RMC}^3 \times 365 \times 24 \]  
\[(2.17)\]

The wind resource map shown in Fig. 2.3 indicates both average wind speed and annual average power density. However, there is no unique correspondence between the two quantities.

2.5 Effect of Height on Surroundings:

Wind speed increases with height up to 450m from ground level then it decreases. This is an important fact to utilize in the design of modern wind turbine towers by increasing the tower height and consequently increasing the wind power density.

To estimate wind speed at a certain height from available measurements at another height the following relationship

\[ v(h_2) = v(h_1) \left( \frac{h_2}{h_1} \right)^\alpha \]  
\[(2.18)\]

Where

- \( h_1 \) is the reference height,
- \( v \) wind speed at the reference height
- \( h_2 \) the height at which wind speed \( v_2 \) need to be estimated and
- \( \alpha \) is the friction coefficient of the ground surface.

2.6 Characteristic of Wind Turbine:

Various Characteristics of wind turbine are plotted to have a better understanding.

2.6.1 Power-Speed Characteristic:

Mechanical Power transmitted to the shaft is:

\[ P_m = 0.5 \rho C_p A V_{in}^3 \]  
\[(2.19)\]

Where \( C_p \) is a function of tip speed ratio (TSR)
The direct relationship between Torque and Power is:

\[ T_m = \frac{P_m}{\omega_s} \] (2.20)

Using the optimum values of \( C_p \) and \( \lambda_{opt} \), the maximum value of aerodynamic torque is:

\[ T_m = 0.5 \rho C_p \omega_{opt} \left( \frac{r}{\lambda_{opt}} \right)^{\frac{3}{2}} \omega_s^2 \] (2.21)

The curve shows that for any wind speed the torque reaches peak value at a definite rotational speed, and this maximum torque varies in the order of the square of rotational speed. Generally, the load torque depends on the electrical loading. The torque can be made to vary the square of the rotational speed by choosing the load properly.

Different control techniques such as Pitch angle control, Stall control (active and passive), Power electronic control and Yaw control are used to control the wind.

### 3.1 Power Electronic Converter:

The power electronic (PE) converter has an important role in modern WECS with variable-speed control method. The constant-speed systems hardly include a PE converter, except for compensation of reactive power. The important challenges for the PE converter and its control strategy in a variable-speed WECS are:

- Attain maximum power transfer from the wind, as the wind speed varies, by controlling the turbine rotor speed, and Change the resulting variable-frequency and variable-magnitude AC output from the electrical generator into a constant-frequency and constant-magnitude supply which can be fed into an electrical grid.

### 3.2 Selection of Converter

This section provides problems and solutions for sizing AC/DC converter and DC/AC inverter used in the wind turbine system shown in Fig. 3.1

![Fig.3.1 Wind turbine system](image-url)

#### 3.2 Required Data:

1. **Wind turbine characteristics:**
   - 500 kW, Rotor speed 16 – 15.4 r.p.m.
2. **Generator characteristics:**
   - PM synchronous generator, rated rms line-neutral voltage 120 V, 140 poles, speed 16 – 15.4 r.p.m.
3. **DC-bus characteristics:** 600 V nominal.

It is required to size the AC/DC and DC/AC converters for the system.

**On the basis of requirement converter divided in two part:**

### 3.3 Grid side Converter:

Converters used in grid side are thyristor converters. They have high power capacity and mainly used in high power applications.

### 3.4 Standalone Converter:

Standalone converter system used PWM control method general. IGBT is mainly used semiconductor because of turn-off capability. PWM converter may produce harmonics and interharmonics due to high frequency switching. Filters are connected to remove harmonics.

DC-DC converters used in standalone side are following:

1. DC boost converter.
2. DC buck-boost converter.

Grid connected topologies with PMSG are classified on the basis of **grid side converters**:

- 3.3.1 Thyristor grid side converter
- 3.3.2 Hard switched grid side converter
- 3.3.3 Matrix converter
- 3.3.4 Multilevel converter
- 3.3.5 Z-source inverter

### 4.1 Common Generator types in Wind Turbine:

The function of an electrical generator is providing a means for energy conversion between the mechanical torque from the wind rotor turbine, as the prime mover, and the local load or the electric grid. Different types of generators are being used with wind turbines. Small wind turbines are equipped with DC generators of up to a few
kilowatts in capacity. Modern wind turbine systems use three phase AC generators [23]. The common types of AC generator that are possible candidates in modern wind turbine systems are as follows:

4.1.1 Squirrel-Cage (SC) rotor Induction Generator (IG),
4.1.2 Wound-Rotor (WR) Induction Generator,
4.1.3 Doubly-Fed Induction Generator (DFIG),
4.1.4 Synchronous Generator (With external field excitation), and
4.1.5 Permanent Magnet (PM) Synchronous Generator.

4.1.3 Doubly Fed Induction Generator:

Currently DFIG wind turbines are increasingly used in large wind farms. A typical DFIG system is shown in the below figure. The AC/DC/AC converter consists of two components: the rotor side converter \( C_{\text{rotor}} \) and Grid side converter \( C_{\text{grid}} \). These converters are voltage source converters that use forced commutation power electronic devices (IGBTs) to synthesize AC voltage from DC voltage source. A capacitor connected on DC side acts as a DC voltage source. The generator slip rings are connected to the rotor side converter, which shares a DC link with the grid side converter in a so called back-to-back configuration. The wind power captured by the turbine is converted into electric power by the IG and is transferred to grid by stator and rotor windings. The control system gives the pitch angle command and the voltage commands for \( C_{\text{rotor}} \) and \( C_{\text{grid}} \) to control the power of the wind turbine, DC bus voltage and reactive power or voltage at grid terminals.

When the rotor speed is greater than the rotating magnetic field from stator, the stator induces a strong current in the rotor. The faster the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed to the electric grid. The speed of asynchronous generator will vary with the rotational force applied to it. Its difference from synchronous speed in percent is called generator ‘s slip. With rotor winding short circuited, the generator at full load is only a few percent.

With the DFIG, slip control is provided by the rotor and grid side converters. At high rotor speeds, the slip power is recovered and delivered to the grid, resulting in high overall system efficiency. If the rotor speed range is limited, the ratings of the frequency converters will be small compared with the generator rating, which helps in reducing converter losses and the system cost.

Since the mechanical torque applied to the rotor is positive for power generation and since the rotational speed of the magnetic flux in the air gap of the generator is positive and constant for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. \( C_{\text{rotor}} \) and \( C_{\text{grid}} \) have the capability of generating or absorbing reactive power and can be used for controlling the reactive power or the grid terminal voltage. The pitch angle is controlled to limit the generator output power to its normal value for high wind speeds. The grid provides the necessary reactive power to the generator.

4.3 Steady State Characteristic:

The steady state performance can be explained using Steinmetz per phase equivalent circuit model as shown in figure where motor convention is used. In this figure \( v_s \) and \( v_r \) are the stator and rotor voltages, \( i_s \) and \( i_r \) are the stator and rotor currents, \( r_s \) and \( r_r \) are the stator and rotor resistances (per phase), \( X_s \) and \( X_r \) are stator and rotor leakage reactance ‘s, \( X_m \) is the magnetizing reactance and \( s \) is slip.

![Fig 4.1: A DFIG and wind turbine system](image)

![Fig 4.2 steady state equivalent circuit of DFIG](image)
motor circuit by moving $X_m$ to the stator terminal. The rotor current $I_r$ is expressed as

$$I_r = \frac{V_r - \left(\frac{V_f}{s}\right)}{\left(\frac{V_r}{s} + \frac{V_f}{s}\right)^T \frac{1}{s} X_m}$$

(4.1)

The electrical torque $T_e$, from the power balance across the stator to rotor gap, can be calculated from

$$T_e = \left(I_r^2 \frac{1}{s}\right) + \frac{P_r}{s}$$

(4.2)

Where the power supplied, or absorbed by the controllable source injecting voltage into the rotor circuit, that is the rotor active power, $P_r$ can be calculated from

$$P_r = \frac{V_r}{s} I_r \cos \theta$$

(4.3)

$$P_r = \text{Re}\left(\frac{V_r}{s} I_r^*\right)$$

(4.4)

4.3 Torque-Slip Characteristic:

Fig: 4.3 Torque-slip characteristic when the angle of $V_r$ is 0. $|V_r|$ is changing from -0.05 to +0.05 pu.

5.1 Simulation:

5.1.1 Study of WTDFIG 9 MW Wind Farm Connected to a 25KV, 60 Hz System

5.2 Simulation Result of DFIG average model:

Fig. 5.1 MATLAB model of Wind farm DFIG Average Model.

Fig. 5.2 Speed of DFIG.

Fig. 5.3 Active power of DFIG.
6.1 Future Work:
The parameters of the controllers can be improved or advanced control methods can be used in future to improve the stability and dynamic performance of grid connected induction generator.

Multilevel Matrix Converter: A multilevel MC is scalable to higher power and voltage levels. The purpose of using multilevel MC is to improve the energy capture of the wind turbine. Studying the configuration and switching strategy of multilevel MC, and developing a dynamic model of a wind turbine system including a multilevel MC are suggested.

Robust Control of the Wind Turbine System: To identify the wind turbine model parameters, the wind speed statistics should be collected at each operating point during long intervals. The developed model is subject to parameter uncertainty. In order to cope with the model uncertainties and

References: